

Impact of Introduction of *Bactrocera dorsalis* (Diptera: Tephritidae) and Classical Biological Control Releases of *Fopius arisanus* (Hymenoptera: Braconidae) on Economically Important Fruit Flies in French Polynesia

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ABSTRACT Oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), was discovered on Tahiti Island in July 1996. Eradication programs were conducted from 1997 to 2001, but failed. From 1998 to 2006, *B. dorsalis* was recovered from 29 different host fruit from the five Society Islands: Tahiti, Moorea, Raiatea, Tahaa, and Huahine. Analysis of coinfection patterns by *B. dorsalis*, *Bactrocera tryoni* (Froggatt), and *Bactrocera kirki* (Froggatt) suggested *B. dorsalis* had displaced these two species and become the most abundant fruit fly in coastal areas. To suppress *B. dorsalis* populations, a classical biological control program was initiated to introduce the natural enemy *Fopius arisanus* (Sonan) (Hymenoptera: Braconidae) into French Polynesia from Hawaii. Wasps were released and established on Tahiti, Moorea, Raiatea, Tahaa, and Huahine Islands. In guava, *Psidium guajava* L., collections for Tahiti, *F. arisanus* parasitism of fruit flies was 2.1, 31.8, 37.5, and 51.9% for fruit collected for 2003, 2004, 2005 and 2006, respectively. Based on guava collections in 2002 (before releases) and 2006 (after releases), there was a subsequent decrease in numbers of *B. dorsalis*, *B. tryoni*, and *B. kirki* fruit flies emerging (per kilogram of fruit) by 75.6, 79.3, and 97.9%, respectively. These increases in *F. arisanus* parasitism and decreases in infestation were similar for other host fruit. Establishment of *F. arisanus* is the most successful example of classical biological control of fruit flies in the Pacific area outside of Hawaii and serves as a model for introduction into South America, Africa, and China where species of the *B. dorsalis* complex are established.

KEY WORDS oriental fruit fly, *Bactrocera* species, classical biocontrol, competitive displacement

The genus *Bactrocera* consists of at least 440 tephritid species distributed primarily in tropical Asia, Australia and the South Pacific (White and Elson-Harris 1992). Throughout Pacific Island nations, fruit flies have inhibited development of a profitable diversified fruit and vegetable industry for domestic use and foreign export by causing direct damage to crops and requiring expensive postharvest quarantine treatments to permit export of fruits and vegetables. At various times, Pacific Islands have served as a reservoir for introduction of *Bactrocera* spp. into the mainland United States (Vargas and Nishida 1985, Metcalf 1995).

Oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae), is considered to be among the

five most damaging and aggressive pest fruit flies in the world (Leblanc and Putoa 2000). It is distributed throughout Asia, including Bhutan, southern China, India, and Thailand (White and Elson-Harris 1992). *B. dorsalis* is native to tropical Asia and has been accidentally introduced into the Commonwealth of the Northern Mariana Islands in 1935, Hawaii in 1945, Guam in 1948, Nauru in the 1980s, and Tahiti in 1996 (Leblanc and Putoa 2000). One hundred twenty-four hosts of *B. dorsalis* have been recorded for tropical Asia (Allwood et al. 1999). Recently, two species in the *B. dorsalis* complex have become established on two new continents: *Bactrocera carambolae* Drew & Hancock, in Suriname in South America, and *Bactrocera invadens* sp. n. in Kenya in Africa (Drew et al. 2005, Rousse et al. 2005).

Four economically important fruit flies have now become accidentally established in French Polynesia: *Bactrocera kirki* (Froggatt) in 1928, *Bactrocera tryoni* (Froggatt) in 1970, *B. dorsalis* in 1996, and *Bactrocera xanthodes* in 1998 (Leblanc and Putoa 2000). At the time of these studies, *B. dorsalis* had been reported only in the Society Islands and *B. xanthodes* only in the

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Austral Islands. Circumstantial evidence suggests that *B. dorsalis* was introduced into French Polynesia from Hawaii. Large-scale eradication programs were conducted on Tahiti and Moorea Islands in 1997. They included applications of methyl eugenol (Steiner et al. 1965) and protein bait (Steiner 1952) with insecticides. After many treatment campaigns, *B. dorsalis* populations were reduced to a few small pockets on both islands. Nonetheless, by 2001, *B. dorsalis* populations rebounded, and, additionally, they spread to other French Polynesia islands of the Society Island group, including Raiatea, Tahaa, and Huahine.

B. dorsalis, introduced into Hawaii in 1945 (van Zwaluwenberg 1947), is the most abundant and widely distributed fruit fly in Hawaii. Studies suggested that 95% of the population develops in common guava, *Psidium guajava* L., and strawberry guava, *Psidium cattleianum* Sabine, and that population cycles are determined primarily by guava fruiting cycles (Newell and Haramoto 1968, Vargas et al. 1983b). During population peaks, commercial and backyard fruit may be severely damaged by *B. dorsalis*. With the introduction of *B. dorsalis* into Hawaii, the largest program in classical biological control against fruit flies was undertaken to reduce the serious damage occurring in fruit (Clausen et al. 1965). Thirty-two natural enemies were released between 1947 and 1952 (Bess et al. 1961). *Diachasmimorpha longicaudata* (Ashmead) increased rapidly after its release in 1948, but it suddenly lost its dominant position during the latter half of 1949 to *Fopius vandenboschi* (Fullaway), which was later superseded by *Fopius arisanus* (Sonan) (Hymenoptera: Braconidae), a wasp introduced in 1950 from the Malay peninsula with other opiine parasitoids but misidentified initially as *Opius persulcatus* Silvestri (van den Bosch and Haramoto 1951, Ramadan et al. 1992). Since its establishment, *F. arisanus* has resulted in a dramatic reduction in infestation of fruit in Hawaii through a high level of *B. dorsalis* parasitism (65–70%), and it has remained the dominant parasitoid species (Haramoto and Bess 1970). Given its success in Hawaii, *F. arisanus* is the candidate of choice for biological control of *Bactrocera* spp. worldwide. To slow the spread of *B. dorsalis*, a classical biological control program was developed between the United States (Hawaii) and French Polynesia. It was predicted that establishment of *B. arisanus* would limit the present buildup and spread of *B. dorsalis* throughout French Polynesia. It could then serve as a cornerstone for an integrated pest management (IPM) approach to future areawide control or eradication programs with bait sprays and male annihilation. Furthermore, non-target studies in Hawaii suggested limited risk of negative impact by *F. arisanus* to native or beneficial tephritid flies in Tahiti (Duan and Messing 2000).

Reported here are studies on the establishment of *B. dorsalis* and *F. arisanus* in the Society Islands of French Polynesia. Specifically we studied 1) *B. dorsalis* infestation of common host fruit; 2) competitive interactions among *B. dorsalis*, *B. tryoni*, and *B. kirki*; and 3) establishment of the natural enemy *F. arisanus* through introductions from Hawaii.

Materials and Methods

Estimating Fruit Fly Abundance. Fruit of *P. guajava*, *Inocarpus fagifer* (Parkinson) Fosberg (Polynesian chestnut), *Terminalia catappa* L. (tropical almond), and *Mangifera indica* L. (mango) were commonly encountered and collected along major roadways of Tahiti Island. Infestation by different fruit fly species was studied in detail to determine fruit fly interactions during a 7-yr period. Other host fruit in various quantities were collected sporadically throughout the year, but because of unpredictable fruiting patterns and scattered distribution of trees along roadsides, numbers of fruit sampled varied. Fruit were weighed and placed in batches on wire metal screen (43 by 28 by 6 cm) inside plastic holding boxes (50 by 32 by 15 cm) that contained 1.5 cm of sand. Fruit were held for 3 wk. Sand from fruit holding boxes was sifted weekly. Pupae were transferred to smaller plastic containers and held until emergence of flies or parasitoids. Fruit and recovered pupae were held in a room maintained at $22 \pm 5^\circ\text{C}$, ambient relative humidity (40–90%), and a photoperiod of 12:12 (L:D) h. Numbers of fruit flies and parasitoids that emerged were recorded.

Estimating Impact of *F. arisanus* Releases. *F. arisanus* were from a colony maintained for 150 generations at the United States Department of Agriculture (USDA), Agricultural Research Service (ARS), Pacific Basin Agricultural Research Center (PBARC) facility in Honolulu, HI. Ten shipments of *F. arisanus* (of $\approx 50,000$ each for a total of 523,127 wasps) inside fruit fly pupae were made by airplane to Tahiti Island between December 2002 and October 2004. Parasitoids were transferred from Fa'a International Airport to the Service du Developpement Rural Laboratory in Papara, Tahiti. A small laboratory was established at Papara for evaluating parasitism in the field, rearing small numbers of fruit flies, and rearing wasps for augmentative releases of *F. arisanus* according to the methodology of Harris and Okamoto (1991). Parasitoids were allowed to eclose from pupae placed inside cubical cages (26 by 26 by 26 cm). Approximately 5,000 wasps were held inside each cage until release. Wasps were provided with creamy textured honey (Bradshaws, Sioux Falls, IA) and water. The number of dead parasitoids inside cages after 4 d was recorded to estimate the number of wasps released into field. Generally, cubical cages with $\approx 2,000$ parasitoids were placed under host trees. Cages were opened gently, and parasitoids were allowed to disperse to nearby ripe host fruit. Parasitoids remaining inside cages were removed with a small brush and placed on vegetation. Initial releases were made throughout communities of Tahiti. Numbers of releases and total wasps released by community are summarized in Fig. 1. Subsequent releases were made on the other Society Islands of Moorea, Huahine, Raiatea, and Tahaa. Initially, it was thought that parasitoids would be mass-reared at the Papara laboratory for distribution to other islands. However, *F. arisanus* became so abundant in some fruit on Tahiti Island that it became more cost effective.

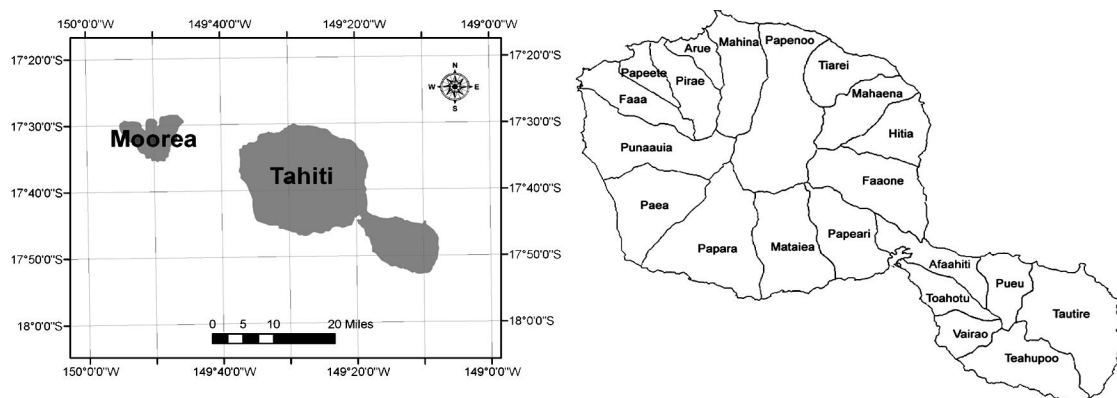


Fig. 1. Map of the two windward Society Islands of Tahiti and Moorea where *B. dorsalis* first became established in French Polynesia, and the 21 communities of Tahiti Island where fruit collections were done to evaluate the spread of *F. arisanus*. Total numbers of *F. arisanus* released (and number of releases) by community were as follows (clockwise): Papara 120,000 (12), Punaauia 13,000 (3), Faa 11,000 (3), Papeete 84,500 (12), Mahina 36,000 (9), Pueu 7,000 (2), Tautire 7,000 (2), Teahupoo 7,000 (2), and Vairao 17,000 (3).

tive to rear wasps from infested fruit and transfer them in small containers with screen tops to other islands.

Data Processing and Statistical Methods. Proportions of *B. dorsalis*, *B. tryoni*, and *B. kirki* flies to emerge from fruit were calculated for four host fruit (*I. fagifer*, *M. indica*, *P. guajava*, and *T. catappa*). Emergence data were pooled for all collection sites by host species and year (1998–2005) on Tahiti Island and 95% confidence intervals calculated by PROC GLM (SAS Institute 1999). For *P. guajava*, *I. fagifer*, and *T. catappa* fruit collections throughout Tahiti Island, data for numbers of *B. dorsalis*, *B. tryoni*, and *B. kirki* recovered from fruit were pooled by year (1998–2006), and fruit fly species per kilogram calculated. Percentage of parasitism by *F. arisanus* (number of adult *F. arisanus* \times 100 / (number of adult *B. dorsalis* + *B. tryoni* + *B. kirki* + *F. arisanus*)) was calculated for the years 2003–2006. To determine the impact of *F. arisanus* on fruit fly species, fruit fly (*B. dorsalis*, *B. tryoni*, and *B. kirki*) emergence per kilogram of fruit was compared for 2002 (before *F. arisanus* releases) and 2006 (after *F. arisanus* releases) as a percentage of decrease in infestation for *P. guajava*, *I. fagifer*, and *T. catappa* fruit collections.

Results

Fruit Fly Host List. During surveys from 1998 to 2005, *B. dorsalis*, *B. tryoni*, and *B. kirki* were recovered from 29, 32, and 23 species of host fruit (Table 1), respectively. All three species coinfecting 20 host plants; *B. dorsalis* and *B. tryoni* coinfecting 27 host plants; *B. dorsalis* and *B. kirki* coinfecting 22 host plants; and *B. tryoni* and *B. kirki* coinfecting 20 host plants. *F. arisanus* was recovered from 15 different host plant species.

Competitive Interactions among *B. dorsalis*, *B. tryoni*, and *B. kirki*. Ripe *I. fagifer*, *M. indica*, *P. guajava*, and *T. catappa* fruit were commonly collected along major roads of Tahiti Island from 1998 to 2005 and held

for emergence of fruit flies. The relative abundance (proportion and 95% confidence interval) of fruit flies based on emergence from *I. fagifer*, *M. indica*, *P. guajava*, and *T. catappa* fruit collected from 1998 to 2006 is summarized in Table 2. *B. dorsalis* increased from 0.7 to 78.3% in *I. fagifer*, from 0 to 97.7% in *M. indica*, from 0.2 to 56.0% in *P. guajava*, and from 0 to 34.8% in *T. catappa*. *B. tryoni* decreased from 65.2 to 16.9% in *I. fagifer*, from 73.8 to 2.3% in *M. indica*, from 86.7 to 42.0% in *P. guajava*, and from 79.6 to 57.5% in *T. catappa*. *B. kirki* decreased from 34.1 to 4.8% in *I. fagifer*, from 26.2 to 0% in *M. indica*, from 13.1 to 2.1% in *P. guajava*, and from 20.3 to 7.7% in *T. catappa*.

Parasitism and Suppression of Fruit Flies. For collections of *P. guajava* fruit for Tahiti Island, *F. arisanus* parasitism was 2.1, 31.8, 37.5, and 51.9% for fruit collected during 2003, 2004, 2005, and 2006, respectively (Table 3). From 2002 (before parasitoid releases) to 2006 (after parasitoid releases), there was a subsequent decline in numbers of fruit flies emerging (per kilogram of fruit) by *B. dorsalis*, *B. tryoni*, and *B. kirki* of 75.6, 79.3, and 97.9%, respectively. For all collections of *I. fagifer* fruit for Tahiti Island, *F. arisanus* parasitism of fruit flies was 2.4, 9.2, 38.8, and 42.0% for 2003, 2004, 2005, and 2006, respectively (Table 4). From 2002 to 2006, there was a subsequent decline in numbers of fruit flies emerging (per kilogram of fruit) by *B. tryoni* and *B. kirki* of 69.0 and 94.0%, respectively. There was no decline in numbers of *B. dorsalis* emerging from this fruit. For all collections of *T. catappa* fruit for Tahiti Island, *F. arisanus* parasitism of fruit flies was 0.6, 5.6, 12.3, and 49.8% for 2003, 2004, 2005, and 2006, respectively. From 2002 to 2006, there was a subsequent decline in numbers of fruit flies emerging (per kilogram of fruit) by *B. dorsalis*, *B. tryoni*, and *B. kirki* of 65.8, 80.2, and 91.8%, respectively. During 2006, mean \pm SD *F. arisanus* parasitism for fruit flies infesting *P. guajava*, *I. fagifer*, and *T. catappa* fruit was $47.9 \pm 5.2\%$.

Table 1. Continued

Fruit family and species	Common name	B. tryoni					B. kirki					B. dorsalis					F. arisanus				
		1998	1999	2000	2001	2002	2003	2004	2005	1998	1999	2000	2001	2002	2003	2004	2005	2003	2004	2005	
Rutaceae																					
<i>Citrus latifolia</i> Tan.	Tahiti lime				x																
<i>Citrus maxima</i> (Burm. f.) Merr.	Pomelo	x	x	x	x	x	x	x													
<i>Citrus reticulata</i> Blanco	Mandarin orange	x			x																
<i>Citrus sinensis</i> (L.) Osbeck.	Orange	x		x																	
<i>Poncirus trifoliata</i> (L.) Raf.	Trifoliate orange				x																
Santalaceae																					
<i>Santalum</i> sp.	Sandalwood																				
Sapindaceae																					
<i>Pometia pinnata</i> J. R. Forster & G. Forster	Pacific lychee	x	x	x		x															
Sapotaceae																					
<i>Chrysophyllum camito</i> L.	Star apple																				
<i>Pouteria camito</i> Radlk.	Abiu					x		x													
Solanaceae																					
<i>Capiscum annuum</i> L.	Pepper																				
<i>Lycopersicon esculentum</i> Mill.	Tomato	x		x																	

Although *F. arisanus* was released along the coast in only nine communities, it spread rapidly and was recovered from 21 of 21 communities on Tahiti Island within 3 yr (Table 5). In February 2006, during a 3-d-survey of four outer Society Islands, where *B. dorsalis* was established and wasps were released, *F. arisanus* was reared from fruit collected on Moorea, Huahine, Tahaa, and Raiatea Islands (Table 6). Furthermore, on Tahaa Island, *F. arisanus* was observed ovipositing on wild *P. guajava* fruit and on *C. papaya* fruit at two farms, suggesting widespread establishment throughout Tahaa Island, where a single release had been made during October 2004. Adult *F. arisanus* also were observed ovipositing into *C. papaya* fruit in orchards on Raiatea and Huahine Islands. Similarly, *F. arisanus* was observed ovipositing on wild *P. guajava* fruit on Moorea Island only 3 mo after a single release of wasps in December 2003.

Discussion

Establishment of *B. dorsalis* in French Polynesia and Competitive Interactions with *B. tryoni* and *B. kirki*. The host list for *B. dorsalis* in Hawaii includes 173 plants (USDA 1989, Metcalf and Metcalf 1992). In the most recent host and parasitoid surveys in Hawaii, *B. dorsalis* commonly infested edible tree fruit (*M. indica*, *C. papaya*, and *C. sinensis*) grown along major roadways in backyards and orchards, but it was most abundant in wild *P. guajava* and *P. cattleianum* patches (Vargas et al. 1983b, 1989, 1990, 1993; Stark et al. 1991). In French Polynesia, during surveys from 1998 to 2006 along major roadways, *B. dorsalis* was recovered from 29 different host plant species collected on the five Society Islands of Tahiti, Moorea, Raiatea, Tahaa, and Huahine. There were many species of host plant fruit coinfecting by *B. dorsalis*, *B. tryoni*, and *B. kirki*, allowing for competitive interactions to occur. On the basis of our surveys and fruit collections, infestation patterns for *B. dorsalis* seemed similar to Hawaii, with *B. dorsalis* commonly reared from *M. indica*, *C. papaya*, *C. sinensis*, *T. catappa*, and *P. guajava* fruit collected from trees along roadsides. Furthermore, when *B. dorsalis* became established in Hawaii, it displaced Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann), in many hosts and lowland habitats, and it became the most abundant and widespread fruit fly species throughout the Hawaiian Islands (Bess 1953; Vargas et al. 1983a, 2000). In French Polynesia, on the basis of 6 yr of data for *M. indica*, *T. catappa*, *I. fagifer*, and *P. guajava* fruit infestation patterns, *B. dorsalis* seemed to be displacing both *B. tryoni* and *B. kirki* as the dominant species in these fruit and it is becoming the most abundant and widespread fruit fly species in coastal areas of Tahiti Island. A similar displacement in another fruit fly species complex has been recorded for *B. zonata* in La Réunion Island (Duyck et al. 2006).

Parasitism of Fruit Flies. In surveys of Kauai Island in Hawaii, the egg-pupal parasitoid, *F. arisanus*, constituted 87.5–95.1% of the parasitoid guild and was very common in tree fruit, particularly *P. guajava* and *P. cattleianum* (Vargas et al. 1983b, 1993). Consequently,

Table 2. Proportion of fruit flies (*B. dorsalis*, *B. tryoni*, and *B. kirki*) recovered from *I. fagifer*, *M. indica*, *P. guajava*, and *T. catappa* fruits collected on Tahiti Island from 1998 to 2005

Host and yr	No. collections	Fruit fly species									
		<i>B. dorsalis</i>				<i>B. tryoni</i>			<i>B. kirki</i>		
		No. fruit	No. insects	% total collected	95% CI	No. insects	% total collected	95% CI	No. insects	% total collected	95% CI
<i>I. fagifer</i>											
1998	291	17,760	256	0.7	0.6–0.8	24,772	65.2	64.7–65.7	12,979	34.1	33.7–34.6
1999	45	704	0	0.0	0.0–0.3	625	63.8	60.7–66.9	354	36.2	33.1–39.3
2000	19	565	457	39.0	36.2–41.8	623	53.1	50.2–56.0	93	7.9	6.4–9.6
2002	44	1,359	2,048	52.6	51.1–54.2	1,042	26.8	25.4–28.2	801	20.6	19.3–21.9
2003	88	1,738	6,193	81.7	80.8–82.5	1,154	15.2	14.4–16.0	235	3.1	2.7–3.5
2004	91	1,353	8,970	83.7	83.0–84.4	1,246	11.6	11.0–12.3	495	4.6	4.2–5.0
2005	52	808	4,355	78.3	77.2–79.4	941	16.9	15.9–17.9	267	4.8	4.3–5.4
<i>M. indica</i>											
1998	12	136	0	0.0	0.0–2.8	79	73.8	64.4–81.9	28	26.2	18.1–35.6
1999	61	452	10	22.2	11.2–37.1	35	77.8	62.9–88.8	0	0.0	0.0–6.4
2000	13	108	114	48.9	42.3–55.5	117	50.2	43.6–56.8	2	0.9	0.1–3.1
2002	36	540	887	72.9	70.4–75.4	316	26.0	23.5–28.5	13	1.1	0.6–1.8
2003	86	1,036	3,816	95.8	95.2–96.4	140	3.5	3.0–4.1	26	0.7	0.4–1.0
2004	31	291	906	95.7	94.2–96.9	41	4.3	3.1–5.8	0	0.0	0.0–0.3
2005	15	160	595	97.7	96.2–98.7	14	2.3	1.3–3.8	0	0.0	0.0–0.5
<i>P. guajava</i>											
1998	72	2,352	24	0.2	0.1–0.3	10,666	86.7	86.1–87.3	1,616	13.1	12.5–13.7
1999	26	304	0	0.0	0.0–0.4	464	67.8	64.2–71.3	220	32.2	28.7–35.8
2000	8	203	0	0.0	0.0–0.3	983	93.2	91.5–94.6	72	6.8	5.4–8.5
2002	32	633	4,858	64.0	62.9–65.1	2,051	27.0	26.0–28.0	685	9.0	8.4–9.7
2003	119	1,841	24,038	71.3	70.8–71.8	8,686	25.8	25.3–26.2	988	2.9	2.8–3.1
2004	130	2,347	15,019	69.8	69.2–70.4	6,071	28.2	27.6–28.8	420	2.0	1.8–2.1
2005	55	1,040	3,207	56.0	54.7–57.2	2,406	42.0	40.7–43.3	118	2.1	1.7–2.5
<i>T. catappa</i>											
1998	58	6,845	7	0.0	0.0–0.1	13,023	79.6	79.0–80.3	3,322	20.3	19.7–20.9
1999	50	1,527	12	0.5	0.3–0.9	2,093	91.0	89.8–92.1	195	8.5	7.4–9.7
2000	15	432	2	0.4	0.0–1.3	489	86.9	83.8–89.5	72	12.8	10.1–15.8
2002	11	499	559	43.4	40.6–46.1	582	45.2	42.4–47.9	148	11.5	9.8–13.3
2003	83	2,807	1,844	20.4	19.6–21.3	5,520	61.1	60.1–62.1	1,665	18.4	17.6–19.3
2004	33	836	2,285	49.9	48.5–51.4	1,671	36.5	35.1–37.9	620	13.5	12.6–14.6
2005	21	1,241	813	34.8	32.9–36.8	1,343	57.5	55.5–59.5	179	7.7	6.6–8.8

only this species was selected for introduction into French Polynesia. On Tahiti Island, *F. arisanus* became established throughout the island in 21 of 21 communities within 3 yr. On the basis of *P. guajava*, *I. fagifer*, and *T. catappa* fruit collections, parasitism has averaged ≈50%. In addition, *F. arisanus* became quickly established on the other Society Islands of Moorea, Raiatea, Tahaa, and Huahine by shipping small cages of parasitoids and releasing them in *C. papaya* orchards or in wild *P. guajava* patches.

The polyphagy of *F. arisanus* has been studied extensively (Quimio and Walter 2001). For example, in

Hawaii *F. arisanus* attacks the eggs of *B. dorsalis*, *C. capitata*, and *B. cucurbitae*, but does not develop successfully in *B. cucurbitae* (Haramoto 1953, Nishida and Haramoto 1953). When *F. arisanus* adults emerge from field-collected fruit, they are sometimes accompanied by mixed infestations of fruit fly species, so host relationships cannot be inferred accurately (Snowball and Lukins 1964). However, Vargas et al. (2001) segregated *B. dorsalis* and *C. capitata* pupae from field collections and found *F. arisanus* to also be the dominant *C. capitata* parasitoid in Hawaii. In Australia, Quimio and Walter (2001) were able to rear *F. arisa-*

Table 3. *P. guajava* fruit collection data for Tahiti Island from 1998 to 2006 showing number of collections, number of fruit collected, fruit weight, total pupae recovered, number of pupae per kilogram, species recovered, species per kilogram, and percentage of *F. arisanus* parasitism

Yr	No. collections	No. fruit	Wt (kg)	Total no. pupae	No. pupae/kg fruit	No. <i>B. dorsalis</i>	No. <i>B. dorsalis</i> /kg fruit	No. <i>B. tryoni</i>	No. <i>B. tryoni</i> /kg fruit	No. <i>B. kirki</i>	No. <i>B. kirki</i> /kg fruit	No. <i>F. arisanus</i>	% parasitism
1998	15	176	2.5	17,150	7,014.3	23	9.4	9,939	4,065.0	1,063	434.8		
1999	30	304	26.9	1,022	38.1	0	0.0	464	17.3	220	8.2		
2000	20	203	15.9	1,097	69.1	0	0.0	1,025	64.6	72	4.5		
2001	7	70	7.9	1,300	164.4	151	19.1	842	106.5	117	14.8		
2002	60	641	48.1	11,306	234.9	4,868	101.1	2,049	42.6	687	14.3		
2003	165	1,678	130.0	47,783	367.6	21,940	168.8	8,340	64.2	894	6.9	677	2.1
2004	230	2,344	171.0	53,084	310.4	15,150	88.6	6,126	35.8	420	2.5	10,111	31.8
2005	103	1,074	65.0	15,917	244.8	3,558	54.7	2,123	32.7	124	1.9	3,479	37.5
2006	145	1,484	136.2	16,801	123.4	3,360	24.7	1,202	8.8	43	0.3	4,971	51.9

Table 4. *I. fagifer* and *T. catappa* fruit collection data for Tahiti Island from 1998 to 2006 showing number of collections, number of fruit collected, fruit weight, total pupae recovered, number of pupae per kilogram, species recovered, species per kilogram, and percentage of *F. arisanus* parasitism

Yr	No. collections	No. fruit	Wt (kg)	Total no. pupae	No. pupae/kg fruit	No. B. dorsalis	No. B. dorsalis/kg fruit	No. B. tryoni	No. B. tryoni/kg fruit	No. B. kirki	No. B. kirki/kg fruit	No. F. arisanus	% parasitism
<i>I. fagifer</i>													
1998	577	11,542	1,131.2	42,586	37.6	219	0.2	16,312	14.4	5,846	5.2		
1999	35	704	76.2	1,062	13.9	0	0.0	625	8.2	354	4.6		
2000	28	565	59.0	1,327	22.5	457	7.7	681	11.5	93	1.6		
2001	62	53	5.4	173	32.3	0	0.0	53	9.9	74	13.8		
2002	68	1,359	119.1	6,025	50.6	2,050	17.2	1,042	8.7	803	6.7		
2003	83	1,653	163.4	11,630	71.2	6,151	37.6	1,074	6.6	218	1.3	183	2.4
2004	67	1,339	132.8	18,618	140.3	8,954	67.5	1,242	9.4	495	3.7	1,087	9.2
2005	66	1,321	114.4	15,048	131.5	4,888	42.7	1,091	9.5	278	2.4	3,965	38.8
2006	91	1,820	169.3	13,297	78.5	4,283	25.3	455	2.7	61	0.4	3,468	42.0
<i>T. catappa</i>													
1998	268	5,363	135.3	27,162	200.8	1	0.0	11,211	82.9	2,234	16.5		
1999	75	1,503	34.3	3,030	88.4	12	0.4	1,093	31.9	195	5.7		
2000	23	456	9.0	575	64.1	2	0.2	494	55.0	72	8.0		
2001	1	20	0.3	162	501.5	0	0.0	121	374.6	22	68.1		
2002	25	499	7.1	2,194	308.9	559	78.7	582	81.9	148	20.8		
2003	132	2,636	72.1	12,576	174.4	1,428	19.8	4,902	68.0	1,214	16.8	43	0.6
2004	42	836	23.4	7,408	316.7	2,285	97.7	1,671	71.4	620	26.5	271	5.6
2005	219	4,376	84.6	15,546	183.7	961	11.4	4,975	58.8	2,296	27.1	1,156	12.3
2006	100	1,983	47.7	6,771	142.0	1,283	26.9	774	16.2	83	1.7	2,121	49.8

nus on *B. tryoni* in the laboratory, and it also has been recovered from the field (Snowball and Lukins 1964). Although we could not confirm parasitism in the field because of mixed fruit fly infestations, we were able to rear *F. arisanus* on *B. tryoni* in the laboratory. We suspect that, as was the case in Hawaii with *C. capitata*, *F. arisanus* will eventually adapt and impact *B. tryoni* in the field. However, we were not able to rear *F. arisanus* on *B. kirki* in the laboratory. Studies are currently underway to segregate field-collected *B. tryoni* and *B. dorsalis* pupae recovered from the field to determine the exact impact of *F. arisanus* on *B. tryoni*. Furthermore, parasitism of *B. tryoni* and *B. kirki* eggs in fruit with mixed infestations may result in signifi-

cant mortality of these species in the egg or larval stage (Bautista et al. 2004).

***F. arisanus* as a Biological Control Agent against Fruit Flies.** The impact of opiine parasitoids in management of fruit flies has been examined in classical, IPM, and augmentative biological control studies. Establishment of natural enemies of invasive tephritid fly pests may have profound impacts in regions otherwise lacking in natural enemies. In Florida, populations of the Caribbean fruit fly, *Anastrepha suspensa* (Loew), decreased by 40% in the years after releases of the parasitoids *Doryctobracon areolatus* (Szepliget) and *Diachasmimorpha longicaudata* (Ashmead) (Baranowski et al. 1993). Perhaps no fruit fly parasitoid has been as successful in suppressing host populations as *F. arisanus* (Rousse et al. 2005). Because of its habit of attacking host eggs, which are more exposed to parasitism than larvae, it can achieve high levels of parasitism, often surpassing 50% in the field (Vargas et al. 1993, Purcell et al. 1998). The success of classical biological control against fruit flies in Hawaii, in particular with *F. arisanus*, has been thoroughly reviewed by Rousse et al. (2005). In Hawaii, *F. arisanus* introductions resulted in a 95% reduction in the *B. dorsalis* population, compared with the 1947–1949 peak abundance of *B. dorsalis* (DeBach and Rosen 1991). Furthermore, *F. arisanus* became the major parasitoid of *C. capitata* in Hawaii (DeBach and Rosen 1991, Vargas et al. 2001). Haramoto and Bess (1970) reported that the mean number of fruit fly pupae (*B. dorsalis* and *C. capitata*) collected from *Coffea arabica* L. fruit in Kona, HI, decreased from 23.6 pupae per 100 fruit (8.7% parasitism) in 1949 to 5.2 (66.6% parasitism) in 1969. With this level of impact on infestation level, establishment of *F. arisanus* has reduced the threat of movement of fruit flies to the mainland from Hawaii.

Table 5. Location (by community), date, number released, and recovery of *F. arisanus* on Tahiti Island

Location	Date and no. of releases	Total no. released	First recovery date
Afaahiti			Jan. 2004
Arue			April 2003
Faa	Dec. 2003–Mar. 2004 (3)	11,000	April 2005
Faaone			June 2004
Hitiaa			May 2004
Mahaena			Dec. 2005
Mahina	Jan. 2003–Aug. 2003 (9)	36,000	Sept. 2003
Mataeia			June 2004
Paea			Mar. 2004
Papara	Dec. 2002–Oct. 2004 (12)	120,000	Mar. 2003
Papeari			May 2004
Papeete	Jan. 2003–Mar. 2004 (12)	84,500	Dec. 2004
Papenoo			Feb. 2005
Pirae			Jan. 2004
Pueu	Feb. and Mar. 2004 (2)	7,000	Feb. 2004
Punaauia	Dec. 2003–Mar. 2004 (3)	13,000	Jan. 2004
Tautira	Feb.–Mar. 2004 (2)	7,000	Dec. 2003
Teahupoo	Feb.–Mar. 2004 (2)	7,000	Mar. 2004
Tiarei			Dec. 2005
Toahotu			June 2004
Vairao	Dec. 2003–Mar. 2004 (3)	17,000	Mar. 2004

Table 6. Fruit collection data from the Society Islands of Huahine, Moorea, Raiatea, and Tahaa from Feb. 2006 survey showing fruit fly species recovered and percentage of *F. arisanus* parasitism

Locality	Fruit	No. fruit	Wt (g)	No. pupae	No. <i>B. dorsalis</i>	No. <i>B. tryoni</i>	No. <i>B. kirki</i>	No. <i>F. arisanus</i>	% parasitism
Huahine	<i>A. carambola</i>	18	1,453	63	27	15		21	33
	<i>C. papaya</i>	1	724	11					
	<i>I. fagifer</i>	17	2,123	341	56	8		117	65
	<i>P. caimito</i>	3	475	3					
	<i>P. guajava</i>	23	2,925	1,191	311	156		209	31
Moorea	<i>T. catappa</i>	152	3,933	504	41	130	2	55	24
	<i>P. guajava</i>	79	6,627	578	101	37	1	117	46
Raiatea	<i>C. inophyllum</i>	13	296	0					
	<i>C. papaya</i>	4	3,158	0					
	<i>C. sinensis</i>	8	1,451	0					
	<i>I. fagifer</i>	49	8,611	801	294	178	2	251	35
	<i>P. americana</i>	13	5,079	37	2	2			0
	<i>P. guajava</i>	41	2,418	88	17	33		17	25
	<i>T. catappa</i>	241	4,629	604	60	57	9	224	64
	<i>C. papaya</i>	12	9,573	35	3			8	73
Tahaa	<i>P. guajava</i>	37	2,777	174	8	12		79	80

In the current study, we were able to compare fruit samples before and after releases of *F. arisanus* on Tahiti Island. From 2002 (before parasitoid releases) to 2006 (after parasitoid releases), there has been a decline in numbers of fruit flies emerging (per kilogram of fruit) by *B. dorsalis*, *B. tryoni*, and *B. kirki* of 75.6, 79.3, and 97.9%, respectively. We recognize that much of the decline in numbers of *B. tryoni* and *B. kirki* may have been due to competitive interactions with *B. dorsalis*. However, *F. arisanus* also may have played a role in the decline. The impact of *F. arisanus* releases has not always been as impressive in other locations outside of Hawaii to date (Rousse et al. 2005). For example, *F. arisanus* has been released and recovered in Costa Rica, but the impact has not been high, although little information is available on its present status or distribution on *C. arabica* farms with *C. capitata* infested fruit (Wharton et al. 1981). Similarly, in Australia, *F. arisanus* was introduced from Hawaii and was established on the native *B. tryoni* in 1962, but it reputedly had only a negligible effect (Quimio and Walter 2001). Nonetheless, establishment of *F. arisanus* in French Polynesia against *B. dorsalis* is now the most successful example of classical biological control of fruit flies in the Pacific area outside of the Hawaiian Islands and serves as a model for introduction of this parasitoid into South America and Africa, where *B. carambolae* and *B. invadens* (Drew et al. 2005) have recently become established. In addition, *F. arisanus* is being studied as a possible candidate for classical biological control of the peach fruit fly, *Bactrocera zonata* (Saunders), in Africa and the Indian Ocean region (e.g., FAO/IAEA 2005).

In 1999, USDA-ARS initiated the Hawaii Fruit Fly Areawide Pest Management program to suppress fruit flies below economic thresholds while reducing the use of organophosphate insecticides (Vargas et al. 2003). The major objective was to conserve biological control in economic crops through the use of reduced risk insecticides such as GF-120 Fruit Fly Bait (Dow AgroSciences, Indianapolis, IN) and male annihilation bucket traps by using an areawide IPM approach (Vargas et al. 2001, 2003; Stark et al. 2004; Prokopy et al.

2003). The program has succeeded in reducing the use of organophosphates and conserving biological controls, such as *F. arisanus* and related braconid species, while suppressing fruit flies below economic injury levels. The present program in French Polynesia has reduced damage by *B. dorsalis* and developed a biological base for further development of IPM programs in conjunction with sanitation, reduced risk protein bait sprays, and male annihilation treatments (Vargas et al. 2003).

Finally, numerous studies have demonstrated the feasibility of parasitoid augmentation for fruit fly suppression (Harris et al. 2000). In Hawaii, release of *Diachasmimorpha tryoni* (Cameron) (at 20,000 per km² per week over a 14-km² area) more than tripled *C. capitata* parasitism rates (Wong et al. 1991). In releases of *P. fletcheri* against melon fly, inside field cages, numbers of melon flies emerging from fruit placed inside treatment cages were reduced up to 21-fold, and numbers of parasitoids were increased 11-fold (Vargas et al. 2004). In open field releases of *P. fletcheri* into ivy gourd patches throughout the Kailua-Kona area, parasitism rates were increased 4.7 times in release plots compared with those in control plots. However there was no significant ($P > 0.05$) reduction in emergence of flies from fruit. In Florida, release of 20,000–60,000 *Diachasmimorpha longicaudata* (Ashmead) per week (in 5- and 13-km² areas) reduced populations of Caribbean fruit fly by 95% (Sivinski et al. 1996). Other workers in Guatemala have reported successful control of *C. capitata* in 10-ha coffee farms by augmentative release of *D. longicaudata* and sterile insect technique (Cancino-Diaz et al. 1996). In Mexico, aerial releases of *D. longicaudata* resulted in increased parasitization rates in mango orchards and a 2.7-fold suppression of *Anastrepha* spp. populations in backyard orchards (Montoya et al. 2000).

French Polynesia is made up of >118 islands and atolls scattered over ≈2,500,000 km² of ocean. Currently, *B. dorsalis* is confined to the Society Islands. Initially, it was envisioned that *F. arisanus* could be mass reared at an estimated cost of US\$2,000 per

1,000,000 parasitoids (Harris and Bautista 2001) and transferred to other islands as *B. dorsalis* spread throughout French Polynesia. However, when *F. arisanus* became numerous in fruit infested with *B. dorsalis* on Tahiti Island, it became more cost-effective to recover wasps from fruit held inside screened cages and to ship them to the outer islands, than to mass rear them in the laboratory on artificial diet. This approach is now being used for shipments to islands where *B. dorsalis* has spread in French Polynesia. Nonetheless, for approximately US\$100,000, the shipment and establishment of *F. arisanus* in French Polynesia has provided a sustainable program to reduce the impact of *B. dorsalis* that was not obtained with expensive eradication programs. Consequently, establishment of *F. arisanus* has reduced the threat of movement of fruit flies to the mainland from French Polynesia.

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